Appendix B

3D printer characterization

The precision and accuracy of the 3D printing setup used in this study were characterized by analyzing the linearity and correspondence between the dimensions of 3D-printed parts and those of their corresponding CAD source files. Pyramid-like structures (Figure B-1a, b) were printed with each extruder, in their corresponding material. In these experiments, the step height was set to 200 µm. A laser scanning confocal microscope with nanometer level resolution (Keyence VK-X, Keyence, Itasca, IL USA) was used to perform height scans of the printed samples (Figure B-1c). The actual heights and widths of the steps were then extracted from the scans and compared against the CAD-specified dimensions (Table B-I). For the PLA materials, there is excellent correspondence and linearity between printed and CAD dimensions, with the least-squares slopes close to unity, very small offsets, and correlation coefficients close to unity. The soft magnetic nylon also shows good linearity and correspondence, although a higher variability in the measurements can be appreciated. This is a result of the surface roughness of the 3D-printed parts, attributed to the large particle size of the filler (up to 150 µm). This circumstance also motivated the fabrication of characterization pyramids with wider steps, resulting in a decrease in the count of steps that can be measured within the field of view of the confocal microscope.

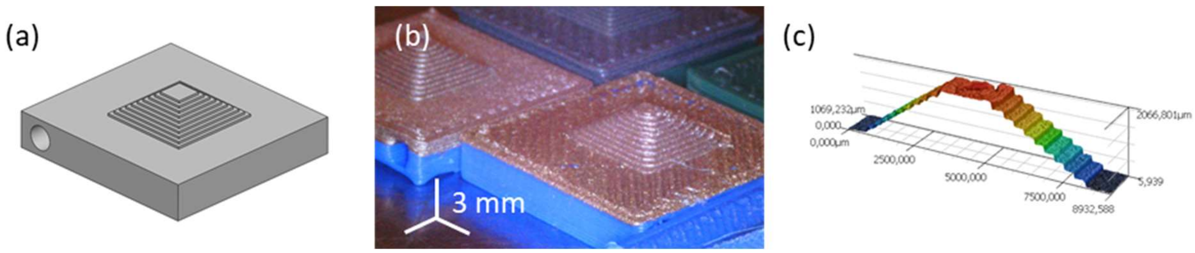
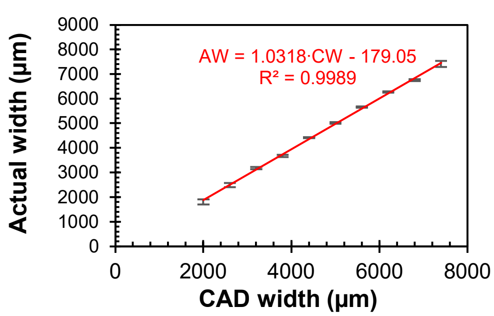


Figure B-1. Computer-generated rendering (a), 3D-printed samples (b), and 3D reconstruction from confocal microscope data (c), of the pyramid-like structure used for characterizing the 3D-printing setup.

Table B-IIV. Least-squares linear fit of width and height measurements of 3D-printed step pyramids versus CAD-specified dimensions. In the plots AW = actual width, AH = actual height, CW = CAD width, CH = CAD height.

<table>
<tr><th>Material</th><th>Width (in-plane)</th><th>Height (out-of-plane)</th></tr>
<tr><td>Dielectric PLA</td><td>



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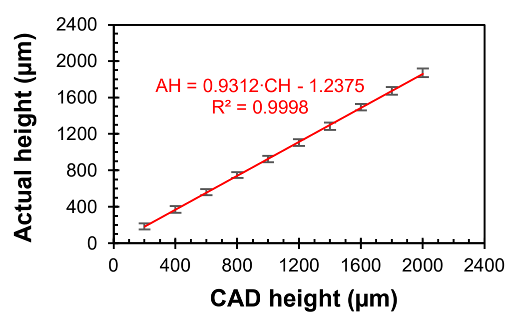

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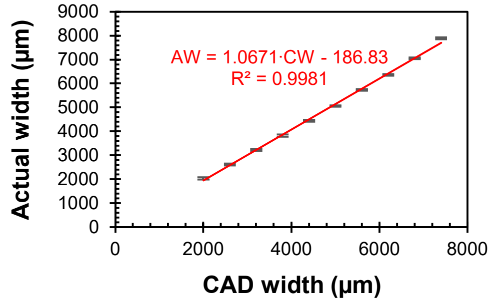
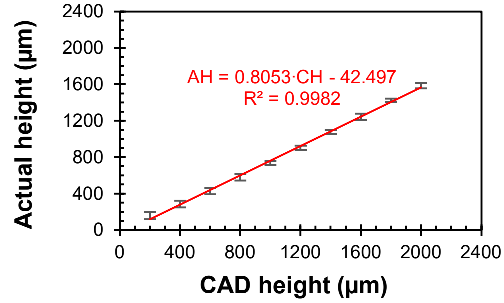
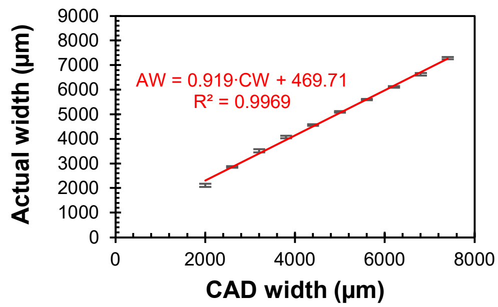
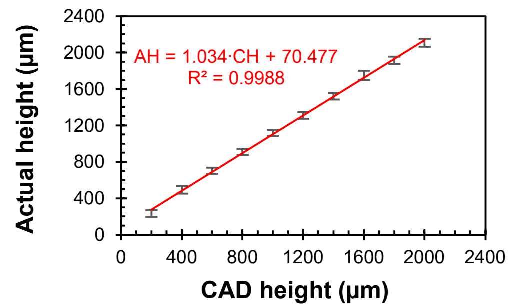
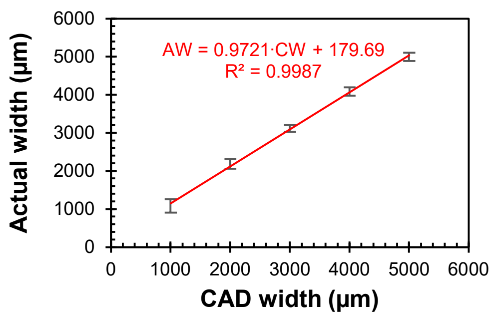
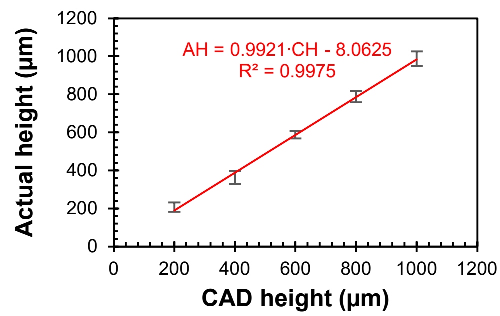
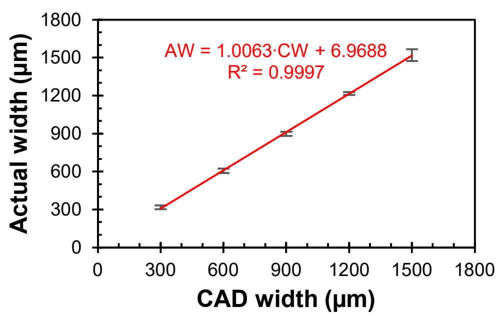
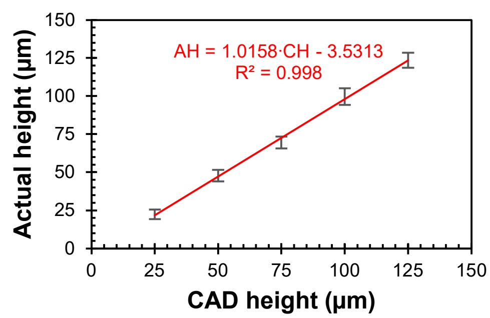
Conductive PLA		
Soft magnetic PLA		
Soft magnetic nylon		

Appendix C

Printing thin insulation films

Achieving electrical insulation between conductive layers is essential for the fabrication of the proposed stacked solenoids. Insulation films must guarantee that there is no electrical contact between adjacent layers (except where deliberately designed for) while being as thin as possible to keep the device compact and enhance its performance. The standard layer height used by cartesian polymer extrusion 3D printers is in the order of 200 µm, while the resolution of the vertical movement of the printing stage is typically in the order of 1 µm. Leveraging those magnitudes, in this study, it was estimated that a layer height of 25 µm would be the approximate limit of what the utilized 3D printing systems could reliably produce. To test the printability of such thin layers, pyramid-like structures similar to those presented in Appendix B were 3D printed with a MakerGear M3-ID 3D printer (MakerGear LLC, Beachwood, OH USA), and their dimensions were measured with a laser scanning confocal microscope (Keyence VK-X, Keyence, Itasca, IL USA) and compared to the CAD-defined dimensions (Table C-I). The data show excellent correspondence between the measurements and the CAD dimensions of the lower steps of the pyramids. However, the 3D printer struggled to print the top steps of the characterization pyramids (Figure C-1). This is attributed to two causes: (i) as 25 µm-high layers are stacked on top of each other, small irregularities accumulate and amplify, ultimately reaching a size that interferes with the correct printing of the layers on top, and (ii) as the surface area of the pyramid steps becomes smaller, the traces to be printed become shorter, which reduces their adherence to previous layers and results in printing defects that become fatal when printing thin layers. Despite this issue, the correct deposition of enough 25 µm-high layers to produce a consistent insulation film (two) was realized.

Table C-I. Least-squares linear fit of width and height measurements of 3D-printed step pyramids versus CAD-specified dimensions. In the plots AW = actual width, AH = actual height, CW = CAD width, CH = CAD height.

Material	Width (in-plane)	Height (out-of-plane)
Dielectric PLA		

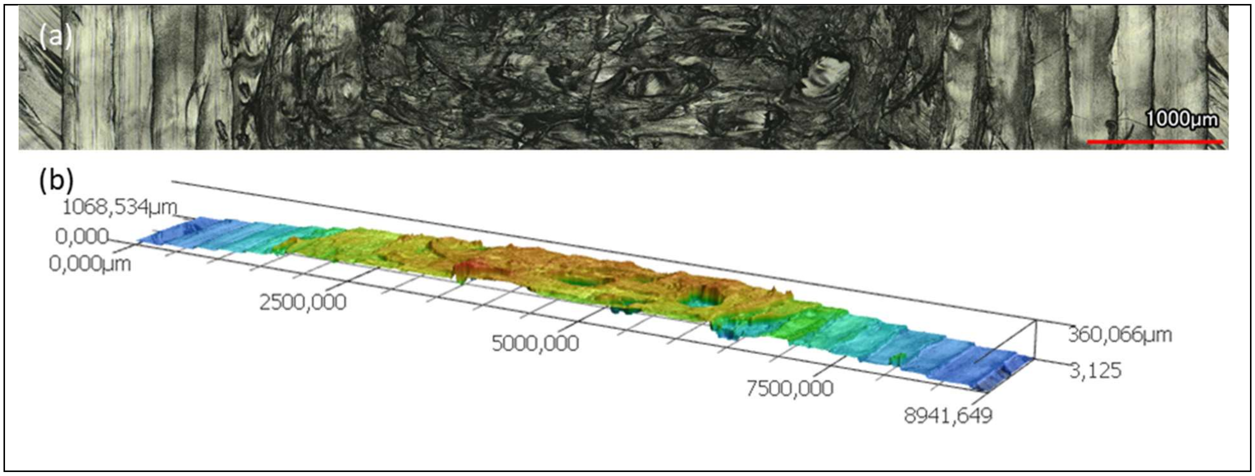


Figure C-1. Confocal microscope imaging (a), and 3D reconstruction (b) of the pyramid-like structure used for characterizing the 3D-printing setup with 25 µm layer height.

After confirming the feasibility of printing two 25 µm-thick thin films on top of each other, optimization of the printing process to reliably 3D print them on top of a discontinuous support (i.e., alternating conductive loops and voids between them) was carried out. The key takeaways from the tunning process can be summarized in three ideas: (i) the dielectric PLA material needs to be over-extruded to ensure consistent electrical insulation, (ii) the deposition speed of the dielectric PLA needs to be low, and (iii) the conductive PLA laying directly underneath an insulation layer must be allowed to cool down before printing on top of it to avoid short circuits [40]. The first two issues were addressed at the G-code level, while the third issue was addressed by installing external cooling fans and adding dummy structures to be printed in dielectric PLA while the conductive PLA features cool down and solidify. Dummy structures were also helpful to avoid oozing issues (also called “stringing” in the 3D printing material extrusion literature) and to prevent the deposition of an excess of melted material at the start of each layer. This can happen when an extruder is idle while still hot, causing melted feedstock to accumulate inside the nozzle and come out in bulk at the start of the next layer, altering the geometry of the 3D printed part. This issue is particularly relevant in multi-material extrusion because each extruder can spend a significant amount of time inactive while other tools are at work, and becomes especially critical when 3D printing very thin layers. By starting to print each layer from a dummy structure rather than directly from the desired part, the excess material is deposited on the dummy structure, and not on the part. When the process requires over-extrusion on the part, the geometry of the dummy structure acquires relevance, as a dense dummy structure could become oversized and interfere with the printing process (e.g., the nozzle can collide with an overgrown dummy structure and detach it from the printer bed). In this work, single wall dummy structures were used to allow lateral overflow of the over-extruded material and prevent the structures from becoming saturated. After optimizing the process, it was possible to reliably 3D print 25 µm-thick dielectric layers on top of a discontinuous surface consisting of alternating traces of 3D-printed conductive PLA and air gaps. Even though this optimization study was carried out using a MakerGear M3-ID 3D printer, the learned lessons were found to be translatable to the E3D ToolChanger working environment.